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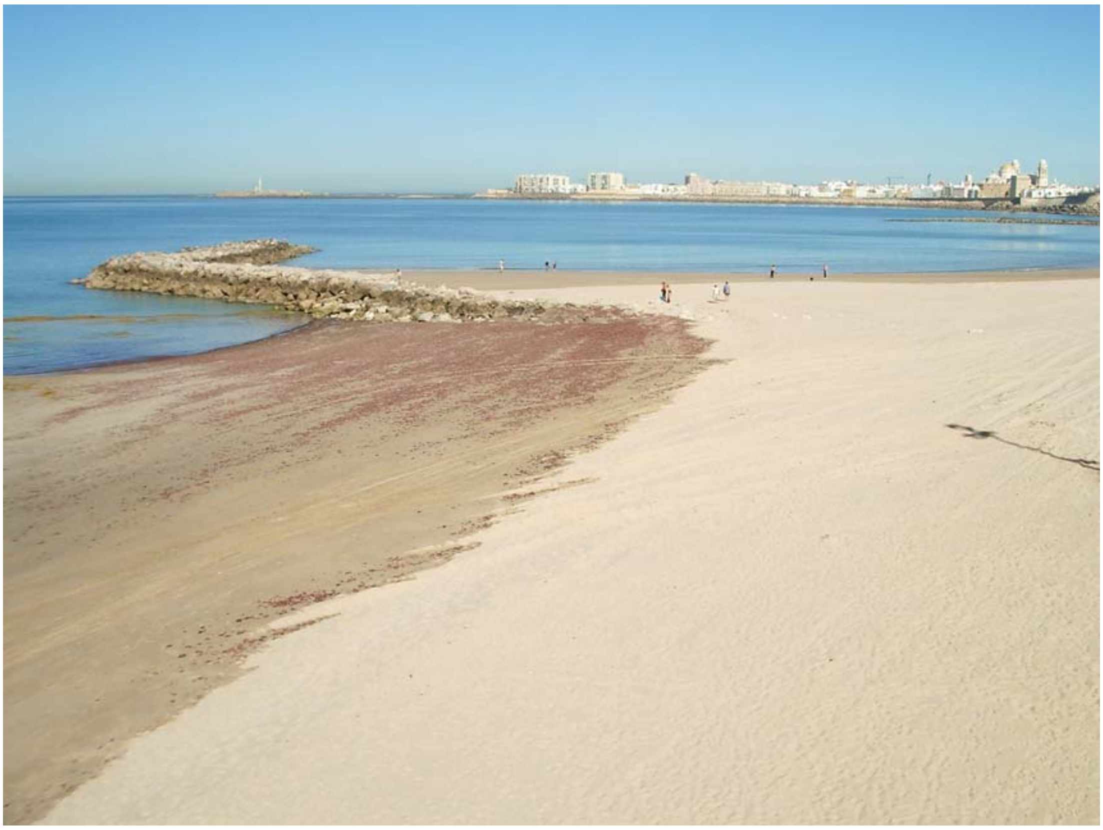
Róbert Jelínek and Elisabeth Krausmann



EUR 23956 EN - 2009

EUROPEAN COMMISSION
Institute for the Protection and Security of the Citizen
TRANSFER Tsunami Risk ANd Strategies For the European Region

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JRC52775

EUR 23956 EN
ISSN 1018-5593

Luxembourg: Office for Official Publications of the European Communities

Printed in Italy

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ABSTRACT

Recent tsunami events with severe consequences have promoted the development of tsunami risk analysis that provides a basis for local authorities to mitigate risk. However, the situation regarding tsunami risk assessment is not favorable as for industrial or other natural hazards. The present tsunami risk analysis applied to the city of Cádiz is based on a general framework for tsunami risk assessment proposed by the Joint Research Centre for the purposes of the TRANSFER project (Jelínek and Krausmann, 2009). The proposed framework involves the following basic steps: scope definition, tsunami hazard analysis, estimation of the consequences of the potential hazard, risk estimation and risk evaluation.

The results of the numerical modeling on tsunami propagation and inundation, hazard and vulnerability analyses are combined to produce tsunami risk zonation maps. In order to characterize the tsunami hazard, the Instituto de Hidráulica Ambiental, Ocean & Coastal Research Group from the University of Cantabria (UCa) together with the Instituto Geográfico Nacional (IGN) generated a series of inundation maps for return periods of 500, 1000, 5000 and 10 000 years. In addition to the specific probabilistic maps, a so-called "worst case" scenario was elaborated using a deterministic approach. The inundation maps served as a basis for the production of tsunami hazard zonation maps. The vulnerability assessment of the population was performed by the Institute for Environment and Human Security of the United Nations University (UNU-EHS) and is based on the three components exposure, coping capacity and susceptibility. Having available the required hazard and vulnerability data allowed us to produce tsunami risk zonation maps for two selected scenarios which are 1) a "5000 year" event and 2) a "worst case" scenario. Furthermore, the tsunami mortality was estimated in order to illustrate the potential for fatalities distributed over the city districts. The results of the tsunami risk analysis will be utilized in applying risk management that should help decision makers to effectively prepare, mitigate and manage this hazard. The mitigation measures that should be taken to reduce tsunami risk may be grouped into two categories: structural and non-structural. The relevant community dealing with risk management has variety strategies to mitigate tsunami risk. In the Cádiz city these are the Spanish Directorate of Civil Protection and Emergency Planning and Demarcación de Costas Andalucia Atlántico Dirección General de Costas.

1. INTRODUCTION

Recent tsunami events with severe consequences have promoted the development of tsunami risk analysis[1] that provides a basis for local authorities to mitigate risk. However, the situation regarding tsunami risk assessment[2] is not favorable as for industrial or other natural hazards. Although there exists a variety of studies focusing on tsunami hazard assessment, tsunami risk assessment has received less attention. This is probably due to the difficulties and uncertainties related to the input data for analysis because tsunamis are a typical example of "low probability – high consequence" events. Generally speaking significant tsunamis occur much less frequently than for example floods, landslides or earthquakes. The majority of tsunamis usually occur in seismically active regions, but theoretically they can be generated in any coastal region due to a variety of trigger mechanisms. To avoid future events, the tsunami phenomenon must be carefully studied and understood.

The present tsunami risk analysis applied to the city of Cádiz is based on a general framework for tsunami risk assessment proposed by the Joint Research Centre for the purposes of the TRANSFER project (Jelínek and Krausmann, 2009). The applied approach uses the results of the numerical modeling, hazard and vulnerability analyses, to produce tsunami risk zonation maps. In order to characterize the tsunami hazard, the Instituto de Hidráulica Ambiental, Ocean & Coastal Research Group from the University of Cantabria (UCa) together with the Instituto Geográfico Nacional (IGN) generated a series of inundation maps for return periods of 500, 1000, 5000 and 10 000 years. In addition to the specific probabilistic maps, a so-called "worst case" scenario was elaborated using a deterministic approach. The inundation maps served as a basis for the production of tsunami hazard zonation maps. The vulnerability assessment of the population was performed by the UNU-EHS and is based on the three components exposure, coping capacity and susceptibility. Having available the required hazard and vulnerability data allowed us to produce tsunami risk zonation maps for two selected scenarios which are 1) a "5000 year" event and 2) a "worst case" scenario. Furthermore, the tsunami mortality was estimated in order to illustrate the potential for fatalities distributed over the city districts. The results of the tsunami risk analysis should help decision makers to effectively prepare,

[1] Risk analysis is described as systematic use of information to identify sources and to estimate the risk. Risk analysis provides a basis for risk evaluation, risk treatment and risk acceptance.
[2] Risk assessment is an overall process of risk analysis and risk evaluation.

mitigate and manage this hazard. In the Cádiz city these are the Spanish Directorate of Civil Protection and Emergency Planning and Demarcacion de Costats Andalucia Atlantico Direccion General de Costas.

In the following we first provide a quick overview of the methodology used to estimate the tsunami risk with specific reference to Cádiz city. This is followed by a description of the results of the tsunami risk analysis. Tsunami mitigation measures for reducing losses are also described in a separate chapter. Recommendations for future research are made in the final part of this report. As it is important to have a common understanding of tsunami risk terminology we summarize some basic terms that we use in the Annex at the end of this report. This report constitutes Annex A8.2.2 of Deliverable D8.2 of the European 6th Framework Programme TRANSFER project.

2. METHODOLOGY FOR TSUNAMI RISK ASSESSMENT

No uniform guidelines exist that specify how to estimate tsunami risk. JRC has therefore examined the current state of knowledge in regards to tsunami risk methods through a literature review (Jelínek and Krausmann, 2009). This review included existing concepts and methods to assess tsunami risk based on examples from the reviewed countries Australia, Canada, Greece, Indonesia, Italy, Japan, New Zealand, Thailand and USA. One of the results of the review was a proposal on a systematic framework for tsunami risk assessment, which involves the following basic steps:

1) Scope definition
2) Tsunami hazard analysis
3) Estimation of the consequences of the potential hazard
4) Risk estimation
5) Risk evaluation

The overall methodology to assess tsunami risk for Cádiz city is illustrated in Figure 1.

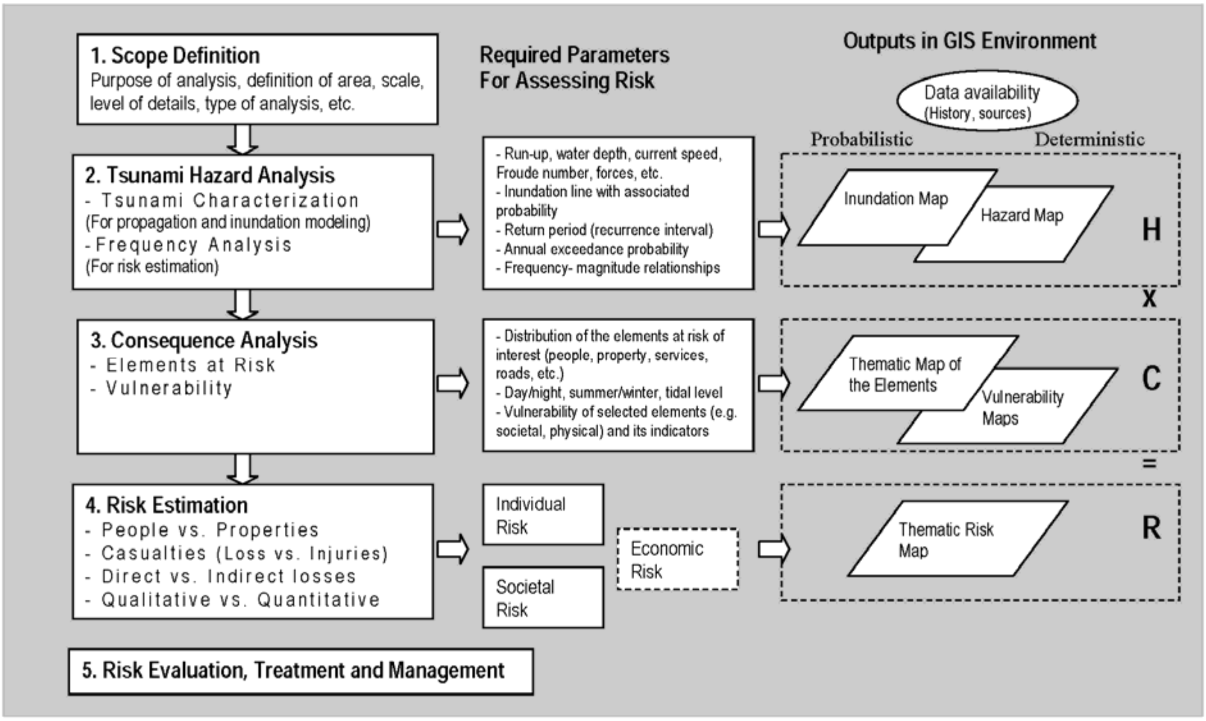


Figure 1: Framework for tsunami risk assessment

The 5 steps that need to be considered for this approach are briefly described below.

1. Scope definition means the definition of the problem to be solved and setting of the basic input parameters for the analysis. We have decided to estimate the tsunami risk for the population, which is distributed in the municipal districts of the Cádiz city. The investigated area of the city is divided into 112 districts, which ranges in size from 7813.6 to 1567805.6 square meters. The analysis is performed in a semi-quantitative way and the results are presented in a qualitative way.

2. Tsunami hazard analysis focuses on both the tsunami phenomenon and its frequency in order to create tsunami hazard maps. The tsunami phenomenon is described by the tsunamigenic sources and their general characteristics needed for propagation and inundation modeling. The UCa and IGN have carried out a set of numerical simulations to produce tsunami inundation maps for return periods of 500, 1000, 5000 and 10 000 years. A detailed description of the numerical modeling and production of inundation maps is discussed in a separate report (UCa-IGN, 2009). The inundation maps include attributes or parameters such as the wave elevation, flow depth, current speed, Froude number and flow forces that are important for tsunami hazard characterization. It is necessary to select the key attributes that best represent tsunami hazard for a specific type of risk analysis, scale or level of investigation. Papadopoulus and Dermentzopoulus (1998) considered the wave surge height and ground elevation range for 4 classes of tsunami hazard severity degree. Other parameters that control a tsunami and can be taken into account for the hazard characterization may include run-up height, wave height, tsunami magnitude, intensity and distance from the source (Rynn and Davidson 1999, Prasad et al. 2000). Jonkman et al. (2008) studied human instability in flowing water as a function of water depth-velocity products. The overall results show that critical depth-velocity products range from 0.6 m^2/s to about 2 m^2/s (Figure 2).

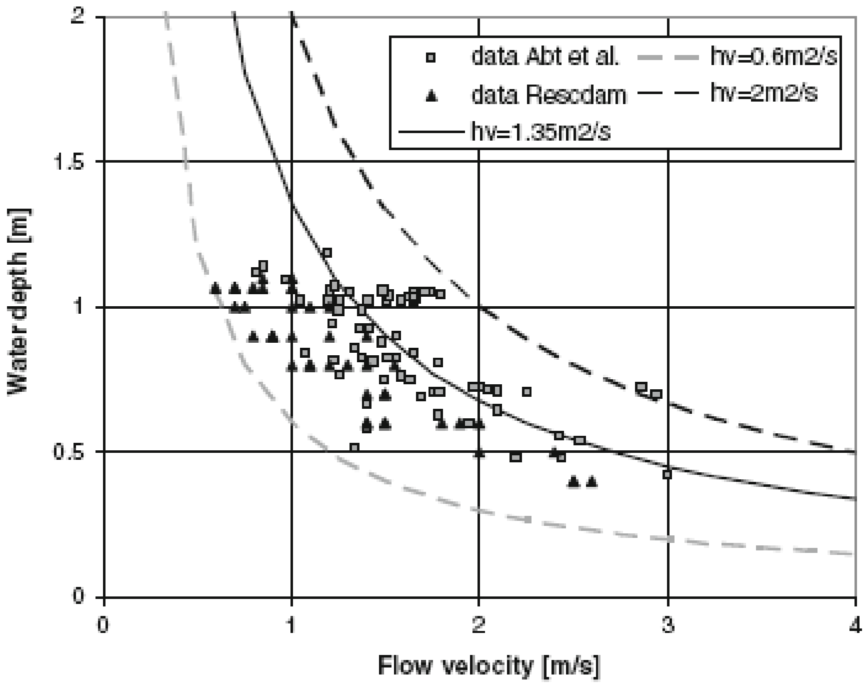


Figure 2: Depth-velocity combinations that resulted in people instability, source: Jonkman et al. 2008

These two parameters are probably the most relevant factors that control people instability in flowing water. Therefore we have decided to use them to characterize tsunami hazard in Cádiz city. The first three hazard ratings are in accordance with the experimental data presented by Jonkman et al. (2008). However, due to the large data range the values higher then 2.0 m^2/s were split into two sub-categories, as shown in Table 1.

Table 1: Tsunami hazard level as a function of depth-velocity relation, based on Jonkman et al. (2008)

Depth-velocity relation [m^2/s]	Description	Assign Score	Hazard level
< 0.6	No danger	1	Very Low
0.6 - 1.35	Danger for some	2	Low
1.35 - 2.0	Danger for most	3	Medium
2.0 - 5.0	Danger for all	4	High
> 5.0	Very dangerous	5	Very high

Each depth-velocity category was assigned a score from one to five with a relevant hazard level to produce the tsunami hazard zonation maps.

For the purposes of the vulnerability and risk analyses, the “5000 year event” and the “worst case” have been selected. The “5000 year event” is based on probabilistic analyses that consider input data uncertainty and variability. A return period of 5000 year corresponds to a probability of 1 in 5000 that the tsunami will occur in any one year. The probabilistic approach is normally based on historical data, however in this case numerical modeling has been applied. The “worst case” scenario represents an aggregation of the inundations obtained for the worst cases generated from each of the five fault sources and includes the distribution function of the tidal level. This scenario does not take into account the probability of occurrence of a tsunami within a specific time period.

3. Consequence Analysis for different scenarios of a potential tsunami includes the identification of the elements at risk, and the vulnerability of the selected risk receptors. The consequences of a tsunami can affect the built, natural and human environment. In this study, the human environment was selected as the element of interest, and therefore the vulnerability assessment is limited to people. No other vulnerability categories, such as property or the environment were analyzed. The vulnerability assessment was performed by the UNU-EHS. According to their methodology, vulnerability is based on the three components exposure, coping capacity and susceptibility. In this approach the vulnerability parameter is independent of the event intensity. More details about the vulnerability assessment are given in a separate report (UNU-EHS, 2009).

4. Estimation of the Risk

Tsunami risk can be expressed and measured in a variety of ways and there is no unique definition of a risk. To assess tsunami risk for the Cádiz city we used the general UNDP (2004) definition of risk as the product of a hazard and its consequences. The consequences can be further defined as a product of the vulnerability of the elements at risk. In mathematical form, the following general expressions are used:

$$R = H \times C\ ,\ (C = V \times E) \qquad 1$$

or

$$R = H \times V\ , \qquad 2$$

where R = risk, H = probability of tsunami hazard occurrence, C = consequence, V = vulnerability, and E = elements at risk.

The two above equations are equivalent but for the tsunami risk analysis in this site we used Eq. 2. We estimated people tsunami risk using a ranking risk matrix, which relates the hazard and the vulnerability. We have decided to use a standard risk matrix of 5 x 5, in which the hazard and vulnerability are weighted equally. The hazard levels are assigned according to Table 1, while the vulnerability scores are based on the UNU-EHS approach (UNU-EHS, 2009). The scores of the hazard and vulnerability are multiplied, and a score from 1 to 25 is assigned to the different risk categories, as illustrated in Table 2.

Table 2: Tsunami risk matrix

Vulnerability	Hazard				
	VL (1)	L (2)	M (3)	H (4)	VH (5)
L (1)	VL 1 x 1 = 1	L 1 x 2 = 2	L 1 x 3 = 3	L 1 x 4 = 4	M 1 x 5 = 5
(2)	L 2 x 1 = 2	L 2 x 2 = 4	M 2 x 3 = 6	M 2 x 4 = 8	H 2 x 5 = 10
M (3)	L 3 x 1 = 3	M 3 x 2 = 6	M 3 x 3 = 9	H 3 x 4 = 12	H 3 x 5 = 15
(4)	L 4 x 1 = 4	M 4 x 2 = 8	H 4 x 3 = 12	H 4 x 4 = 16	VH 4 x 5 = 20
H (5)	M 5 x 1 = 5	H 5 x 2 = 10	H 5 x 3 = 15	VH 5 x 4 = 20	VH 5 x 5 = 25

Risk range: Very Low (=1); Low (2-4); Medium (5-9); High (10-16); Very High (20-25)

The results of the tsunami risk matrix are 5 risk levels. In the very low risk level (VL), both the hazard and the vulnerability are low. While for the very high risk (VH), at least one category of the hazard or vulnerability must be high or very high and the second at least high. In the final step of the analysis the risk matrix is translated in a GIS environment into thematic risk maps.

In addition to the tsunami risk zonation maps, the mortality rate was calculated in order to illustrate potential fatalities distributed over the city districts. The mortality rate function is based on tsunami wave height when it reaches land and the affected population defined by the inundation zone (CDMC, 2003 in Jonkman et al., 2008):

$$F_D = 0.0282 e^{0.2328 h_{ts}} \quad \text{with} \quad F_D \leq 1 \qquad 3$$

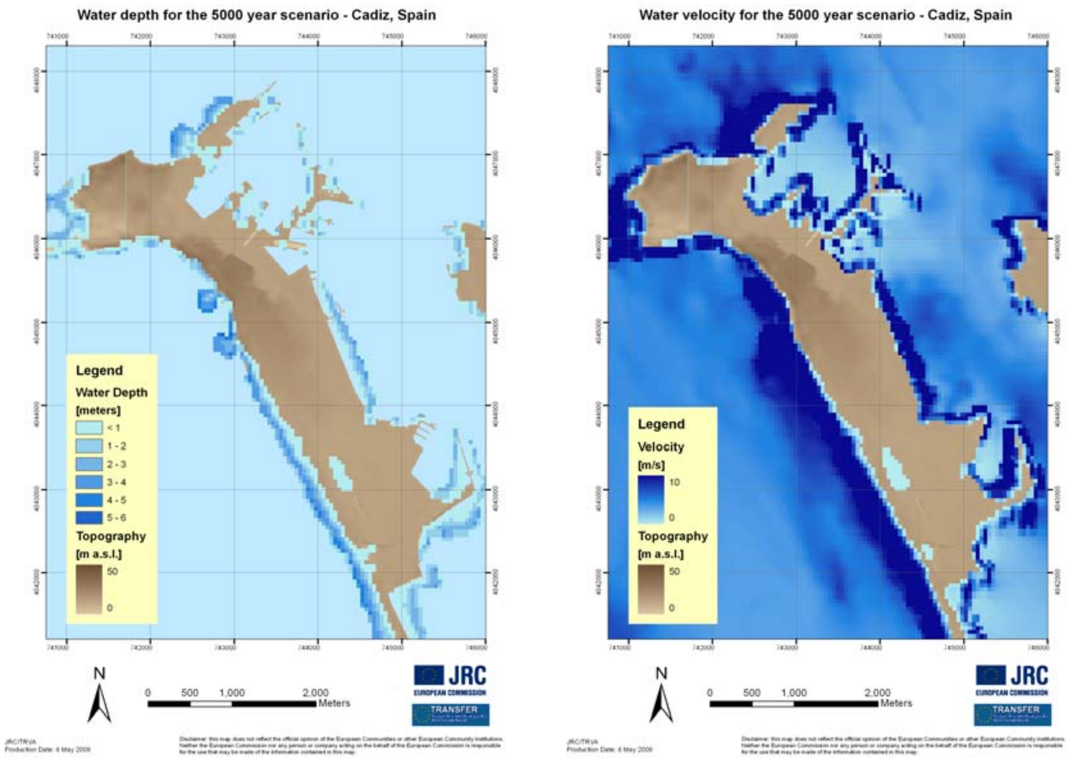
Where, h_{ts} is the tsunami wave height [m]

Using the Eq. 3, a critical tsunami height of 15.3 m was determined, which theoretically causes 100 % of people loss. A higher tsunami will not have any further effect to increase mortality.

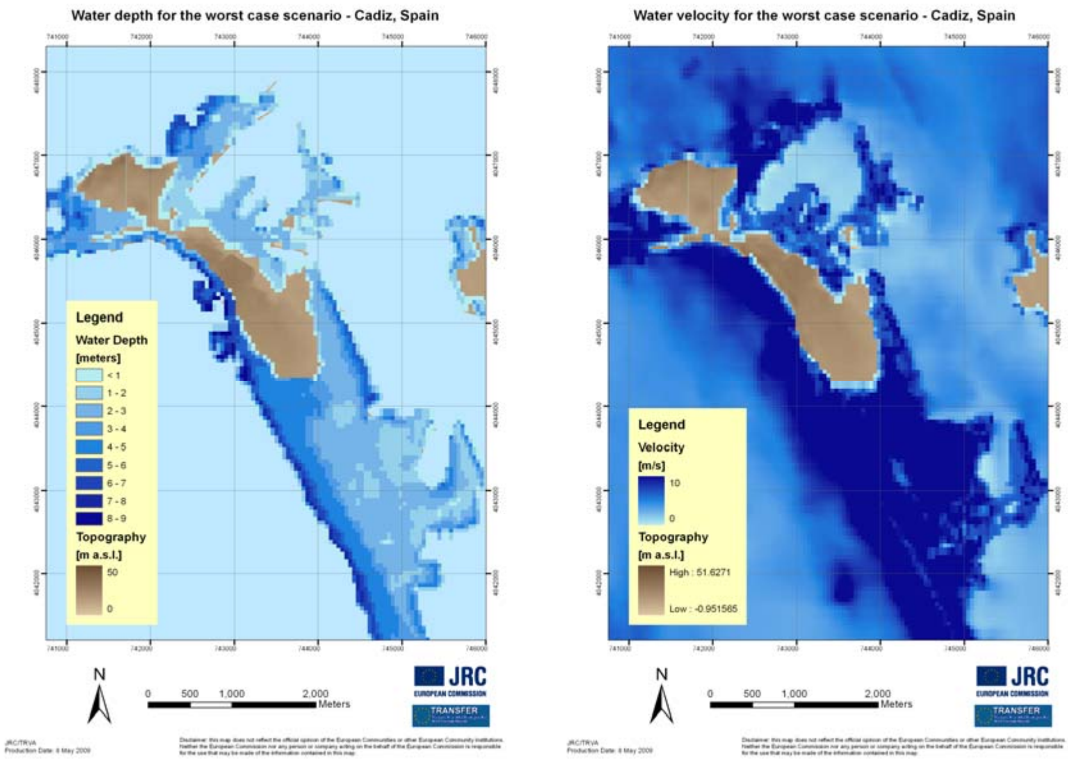
5. Risk Evaluation is the final step in the process of risk assessment in which the estimated level of risk is compared to risk criteria and the acceptability of the risk is determined. If required, options to reduce or mitigate risk can be suggested. The tsunami risk in this study was estimated in a qualitative way, which means that no numerical characterization was used. Therefore, the obtained qualitative risk categories did not allow making a comparison with other risks, for example from other tsunami sites or risk associated with other hazards such as floods, earthquakes, etc.

3. ANALYSIS AND RESULTS

The determination of the tsunami hazard is a preliminary step in the tsunami risk assessment. The level of tsunami hazard was determined using inundation maps and is dependent on the combination of the water depth and velocity of a potential tsunami. Therefore, initially two different thematic maps of the water depth and velocity were generated for two selected scenarios: the “5000 year” and the “worst case”, as shown in Figure 3.



a)

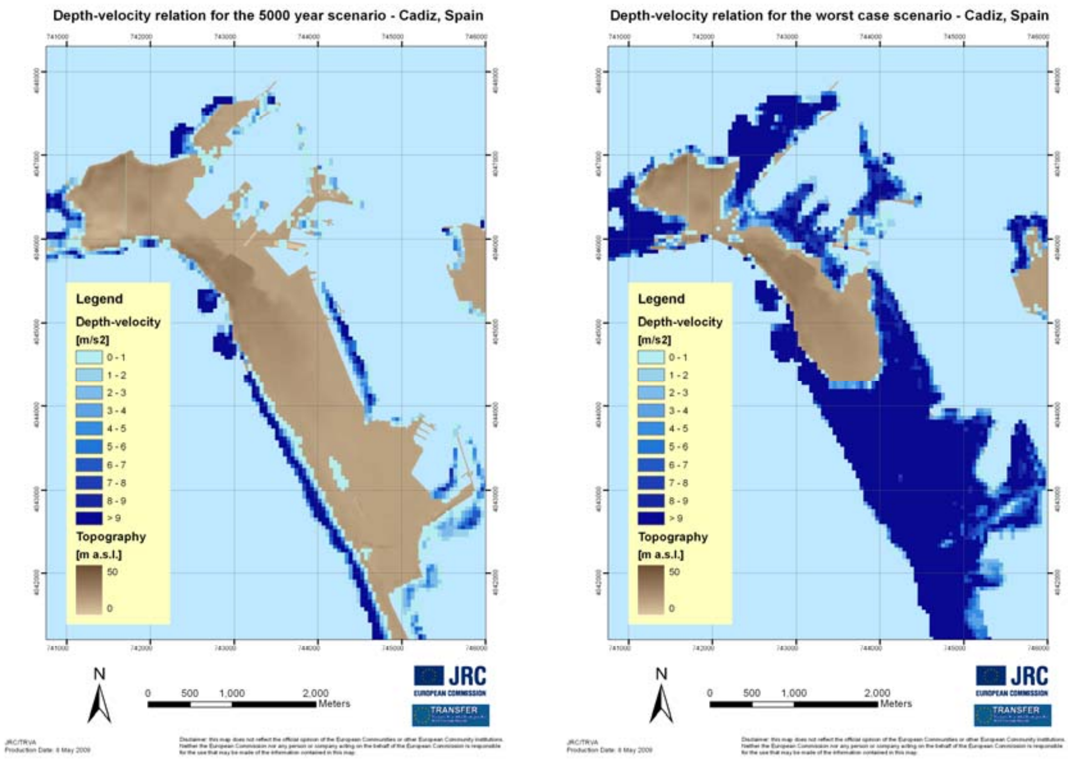


b)

Figure 3: Thematic maps showing the maximum water depth and maximum current velocity for: a) the 5000 year scenario and b) the worst case scenario

Numerical simulations have shown that the values of the physical tsunami parameters are characterized by a wide range of a spatial variation. In our case the water depth varies between 0 to 5.4 m for the “5000 year” scenario, with a maximum of 9.7 m for the “worst case” scenario. The current velocity ranged from 0 to 6.9 m/s with a maximum of 9.9 m/s for the “worst case” scenario. Such high velocities cause erosion and deposition of material, which was however neglected in this study. Darker blue color represents a greater threat with respect to the relevant physical tsunami parameter. It is necessary to consider that the presence of barriers, such as building blocks or flood defense system, which can influence the physical parameters of tsunami, was neglected in this study.

The maximum water depth and the maximum current velocity thematic maps were multiplied to create new depth-velocity maps (see Figure 4) which were used for the tsunami hazard component of the risk analysis.

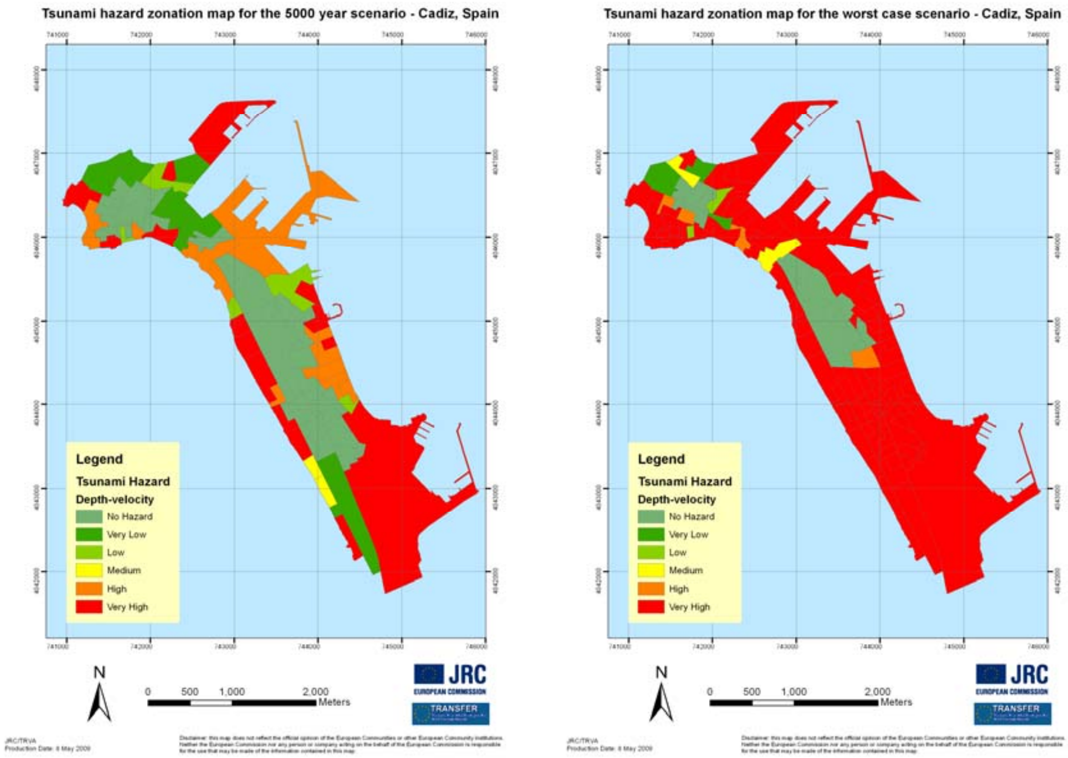


a) b)

Figure 4: Tsunami depth-velocity map for: a) the 5000 year scenario and b) the worst case scenario

The dark blue color in the depth-velocity relation map corresponds to values greater than 9 m/s^2. Such a high value covered most of the area in the southern part of the city in the worst case scenario. In contrast, brawn color represents surface elevation and therefore the part of the city which was not inundated.

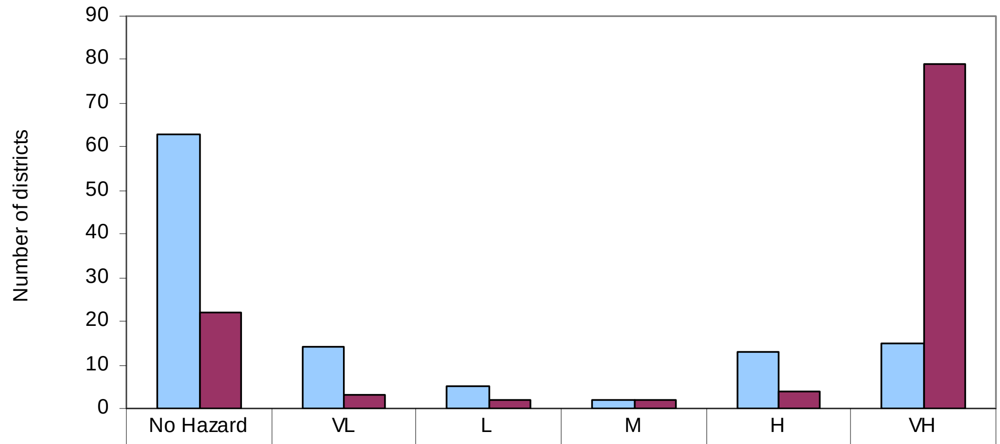
In the next step, the raster depth-velocity maps illustrated in Figure 4 were combined with a thematic map of the municipal districts of Cádiz city. Some assumptions (e.g. the smallest unit was the city district) had to be made due to level of detail used for the analysis. Therefore, we decided to use a conservative approach, where only the maximum value of the water depth-velocity relation was assigned to each corresponding city district. The conservative approach allows us to identify hot spot areas for prioritizing the tsunami risk and for more detailed (for example quantitative) analysis. It is likely that this resulted in an overestimation of the tsunami hazard and subsequently of the risk. The created preliminary maps were further reclassified into the 5 hazard levels (see Table 1) to produce tsunami hazard zonation maps, as illustrated in Figure 5.



a) b)

Figure 5: Tsunami hazard zonation maps: a) 5,000 year event and b) worst case scenario

A five-color scheme was used to represent the tsunami hazard. The red color in the map shows unsafe areas with a very high tsunami hazard, while the green areas are of low or very low hazard. One extra green color shows the areas with no tsunami hazard, which represents non-inundated districts with respect to the investigated scenario. The results for the tsunami hazard were also expressed in the form of a pair column chart illustrated in Figure 6.



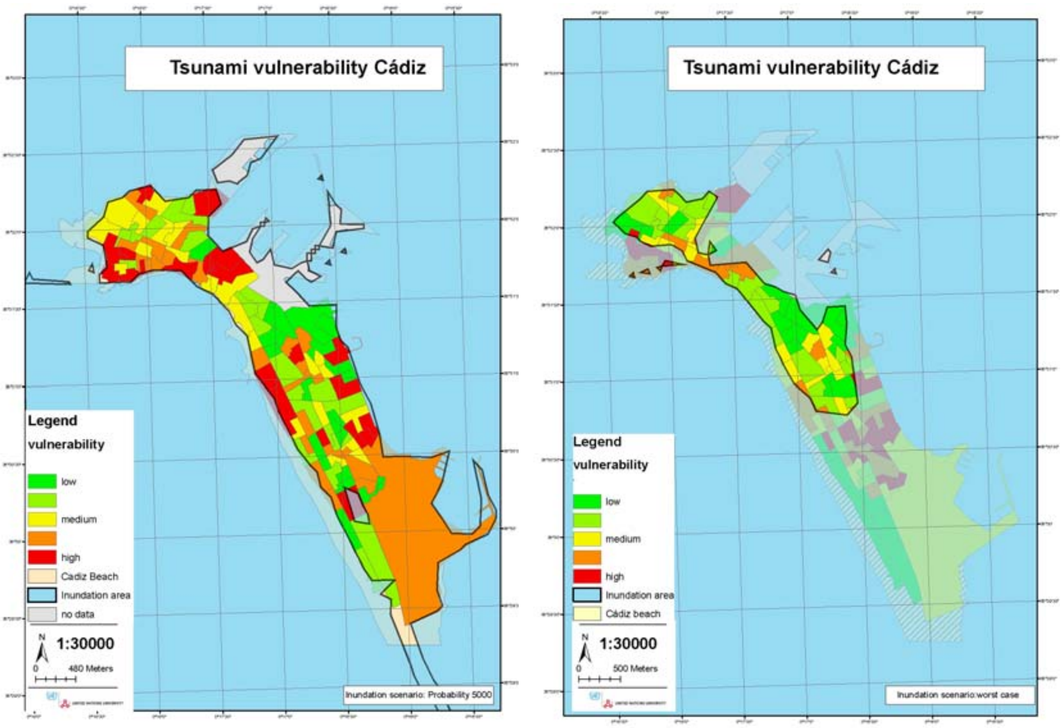
	No Hazard	VL	L	M	H	VH
Hazard 5000	63	14	5	2	13	15
Worst case	22	3	2	2	4	79

Risk Categories

Figure 6: The pair column charts of tsunami hazard zonation for the 5,000 year event (in blue) and the worst case scenario (purple)

This allows us to make a comparison between the two scenarios. The chart clearly shows that the majority of the area (79 districts) is in the very high (VH) tsunami hazard in the “worst case” scenario while only 15 districts lie in the VH zone for the 5000-year event. In contrast, there are 63 districts with “no hazard” in the “5000 year” scenario. The middle segments of the chart show an approximately equal number of districts that are in low (L) or medium (M) hazard zones.

The vulnerability assessment for the population was prepared by the UNU-EHS, and the resulting tsunami vulnerability maps are presented in Figure 7.

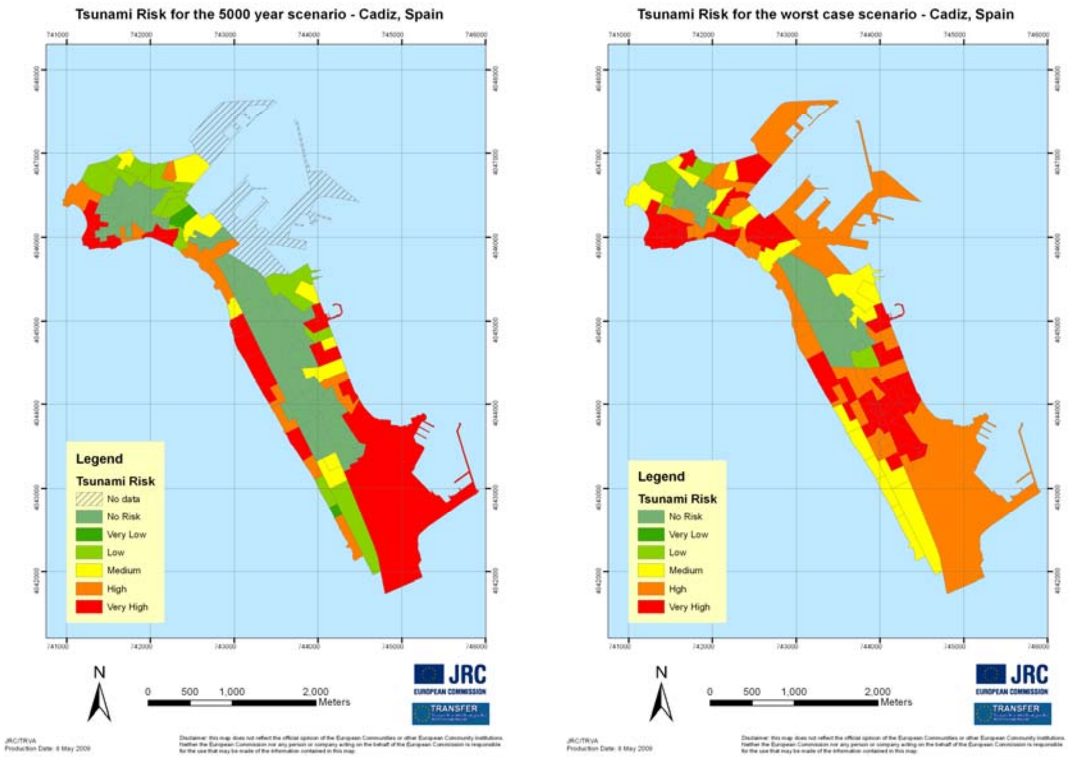


a) b)

Figure 7: Tsunami vulnerability maps for the: a) 5,000 year event and b) worst case scenario (UNU-EHS, 2009)

The general procedure for production and evaluation of the vulnerability maps is discussed in UNU-EHS, 2009. In their study the vulnerability is composed of the three factors: exposure, susceptibility and coping capacity that are equally weighted to produce an aggregated vulnerability. The exposure of Cádiz is calculated for each city district based on the inundation vector data obtained from the UCa. The susceptibility was defined based on two indicators. The first indicator comprises the percentage of population younger than 6 and older than 65 years. The second indicator corresponds to the combination of dependency ratio and gender ratio and states the percentage of total population that has to be supported by the male in working age. To characterize the coping capacity, the percentage of buildings that have more than one level to which people could vertically evacuate, the number of people that have received school education for more than six years and the sum of children less than 6 years, illiterates and non-Spanish-speaking migrants were considered. The first two are positive coping factors, whereas the last one describes a negative coping factor. All three coping factors were equally weighted and summed up to one coping indicator.

Once the tsunami hazard and vulnerability are known, the risk can be estimated by combining the two contributing factors using Eq. 2. The resultant tsunami risk zonation maps are presented in Figure 8.



a) b)

Figure 8: Tsunami risk zonation maps: a) 5,000 year event and b) worst case scenario

The tsunami risk maps illustrate the variable impact of the two selected scenarios. The very high risk districts are located along both coasts in the "5000 year" event, while for the "worst case" various small city districts at very high tsunami risk are concentrated in the central part and also in the historic town of Cádiz city. The hatched grey-color in the "5000 year" risk map refers to "no data" because these data were not available from the vulnerability assessment. The dark green inside of the city reflects "no risk" because this area was not flooded with respect to the selected scenario. Similarly, as for the tsunami hazard, a chart of the tsunami risk zonation is provided in Figure 9 to compare the risk resulting from the 2 analyzed scenarios.

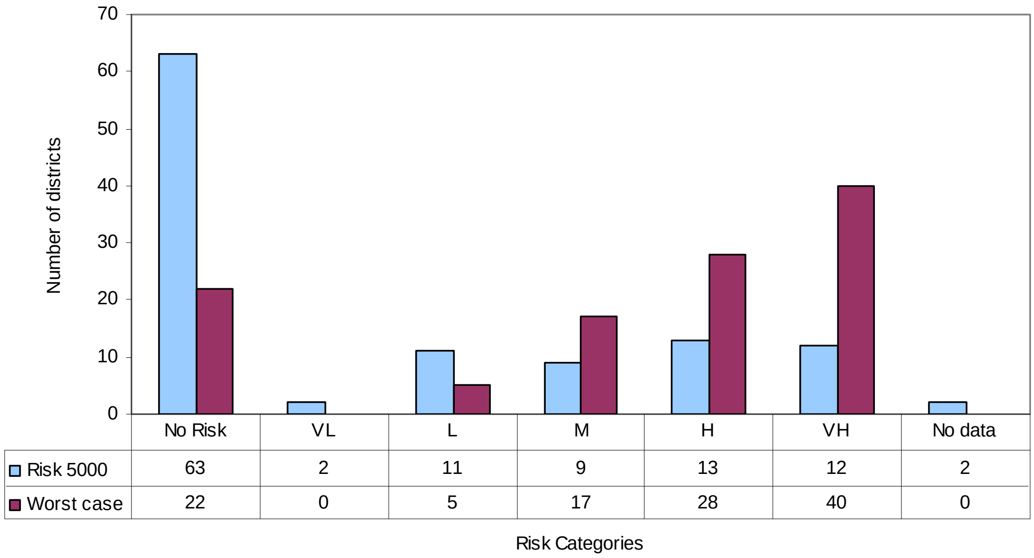


Figure 9: Pair column chart of tsunami risk zonation for the: a) 5,000 year event, and b) worst case scenario

The majority of the city districts or better their flooded proportions are in the very high (VH) or high (H) risk zone for the worst-case scenario. A very high tsunami risk was estimated for 12 districts in the “5000 year” scenario, while 40 districts fall under the VH zone for the “worst case” event. This is due to having used the most conservative values of the physical tsunami parameters for the hazard assessment. For this reason, the resultant risk maps overestimate the risk level. In contrast, there is a relatively high number of districts with “no risk”, which represent the areas that were not flooded with respect to the analyzed scenario.

In addition to the tsunami risk zonation maps, the mortality rate (i.e. the proportion of people who can die) was calculated for the worst case scenario. The calculation is based on the tsunami wave height recorded on the coast and the number of people affected (see Eq. 3). The distribution of the maximum values of the tsunami wave height along the investigated area was obtained by numerical modeling (see also UCa-IGN, 2009). Again, we used a conservative approach and therefore only the maximum wave height was assigned to the relevant city district. The recent population data was obtained from the Instituto Geográfico Nacional, which provides geographical data for Spain. The number of people is simply defined as the proportion of the population present in the affected area in each city district, which is defined by the inundation zone. This allows us to prepare a tsunami fatality map illustrated in Figure 10.

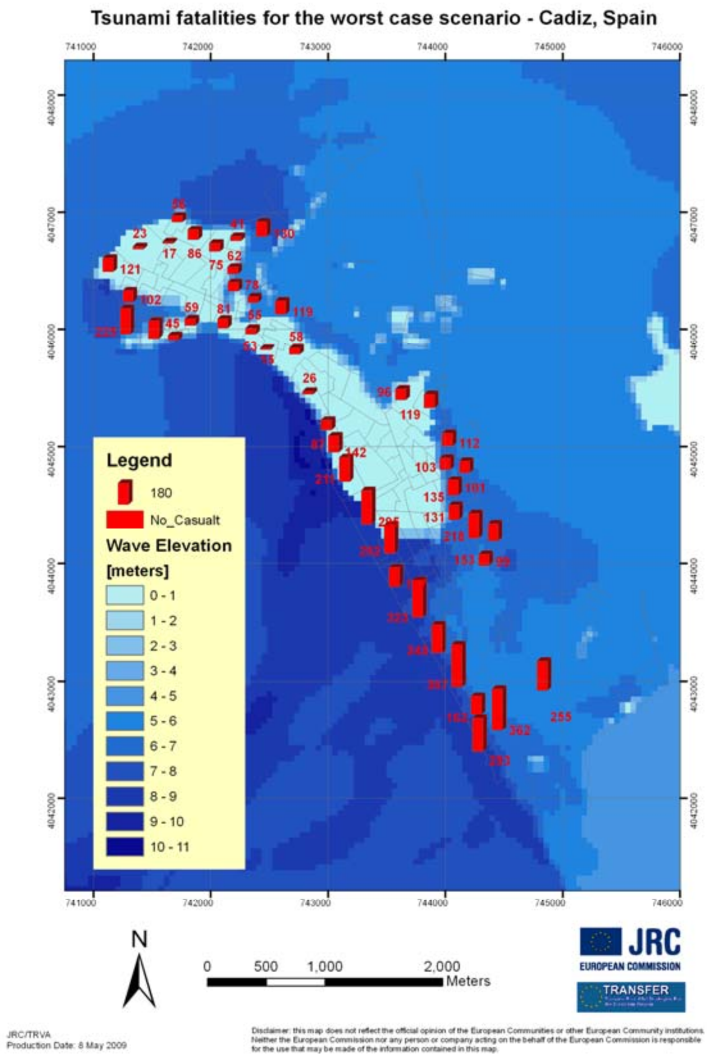


Figure 10: Tsunami fatalities map with maximum tsunami wave height for the worst case scenario

The tsunami fatality map roughly illustrates the distribution of potential fatalities in the Cádiz city. It shows that the highest potential mortality is concentrated along the west coast of the city. This area is also known for its beaches that have higher seasonal population and are therefore the most vulnerable to loss of life. However, in this approach, neither the population changes during the specific time of the year nor location of the people (e.g. inside of buildings or outdoors) were considered. Therefore, we emphasise that the estimated fatalities map have only informative value.

4. TSUNAMI RISK MITIGATION MEASURES

Mitigation activities concern actions taken to reduce or eliminate risk to human life and property based on tsunami risk assessment. This includes planning and zoning to manage development in areas particularly at risk for tsunami, embracing tsunami resistant construction, and protecting critical facilities and infrastructure (NSTC, 2005).

There are various measures to mitigate tsunami risk, which are usually grouped into two general categories: structural and non-structural. Structural mitigation includes reducing risk through measures using engineering solutions such as reinforcing or strengthening of the buildings that may be damaged or cause injury; coastal protection of the area using for example tsunami defense structures or reduction of the impact of tsunami wave prior to reaching the shoreline. Non-structural mitigation provides people with basic information on tsunami risk, education or training, because awareness and preparedness are the most important factors to reduce potential losses due to tsunami. CSSC (2005) summarizes tsunami risk reduction measures in four ways: engineering standards, public education, warning system and evacuation planning. The engineering standards can create buildings and port structures more resistant to the damage. Education can improve knowledge about tsunami risk. This together with the training of the local population to recognize tsunami signs and provide basic instructions on how to respond to a tsunami warning are important steps towards reducing the tsunami risk. Preparedness of the community to tsunami hazard is a long-term process. For example, in Pacific states education begins in schools, where children are taught about the basic elements of earthquake and tsunami safety. Providing information on tsunamis such as educational brochures or guidelines can help improve the knowledge about the tsunami threat and subsequently diminish or eliminate its risk. Warning systems can alert a population to a tsunami coming from a distant source.

A good example of effective tsunami risk management is found in the USA. In 1997 five Pacific States (California, Hawaii, Oregon, Washington and Alaska) together with four Federal Agencies (NOAA[3], USGS[4], FEMA[5] and NSF[6]) established the partnership "The U.S. National Tsunami Hazard Mitigation Program (NTHMP)". The main goal of the

[3] National Oceanic and Atmospheric Administration
[4] United States Geological Survey
[5] Federal Emergency Management Agency
[6] National Science Foundation

NTHMP is mitigation of the tsunami hazard to all threatened U.S. coastal communities. The NTHMP developed a strategic plan for a mitigation project that would promote the development of ‘‘tsunami-resilient communities’’. The plan lists five goals that describe the nature of a tsunami-resilient community. Tsunami-resilient communities should: (1) understand the nature of the tsunami hazard, (2) have the tools they need to mitigate the tsunami risk, (3) disseminate information about the tsunami hazard, (4) exchange information with other at-risk areas, and (5) institutionalize planning for a tsunami disaster (Jonientz-Trisler et al. 2005, Bernard, 2005, Gonzáles et al. 2005). Another example prepared by the NTHMP for local government officials and those responsible for community development to manage the tsunami hazard is summarized in “Seven Principles for Planning and Designing of Tsunami Hazard” (NTHMP, 2001; Eisner, 2005). The Seven Principles are:

1. Know your community's tsunami risk: hazard, vulnerability, and exposure
2. Avoid new development in tsunami run-up areas to minimize future tsunami losses
3. Locate and configure new development that occurs in tsunami run-up areas to minimize future tsunami losses
4. Design and construct new buildings to minimize tsunami damage
5. Protect existing development from tsunami losses through redevelopment, retrofit, and land reuse plans and projects
6. Take special precautions in locating and designing infrastructure and critical facilities to minimize tsunami damage
7. Plan for evacuation

A tsunami risk analysis for the city of Cádiz was performed by combining knowledge of the tsunami hazard with the vulnerability of the population. Therefore, mitigation activities can focus on the reducing the tsunami hazard itself or reducing the vulnerability of the affected population. Tsunamis are almost impossible to predict and locate with a high degree of reliability and therefore it is very difficult to reduce the hazard component. For this reason, the mitigation measures should mainly address the vulnerability, which means reducing the potential consequences of a predicted event.

The development of mitigation measures for the city of Cádiz should concentrate on those zones with very high or high risk. These can include beaches, which can be extremely busy during summer holidays and therefore could have high consequences due to potential tsunami. Other recommended measures are summarized below:

- Conduct a detailed inventory of the critical facilities vulnerable to tsunami hazards in the potential inundation areas. Subsequently, building vulnerability and risk assessment will be needed.
- Public education, training and dissemination of information on tsunami risk should be performed to prepare and protect the community for a potential tsunami event.
- Investigate if a warning system would be appropriate for this area to minimize potential losses due to tsunami.
- Develop an effective evacuation plan or use other measures that can reduce casualties in case of a tsunami event. The evacuation maps should be produced based on the inundation maps. In these maps, the evacuation routes and possible shelter locations should be included.

The choice of recommended mitigation measures is dependent on the preference of the decision makers. It is common practice to combine a variety of the structural and non-structural measures.

5. DISCUSSION AND RECOMMENDATIONS

In order to assess tsunami risk in Cádiz city, we have applied an assessment procedure proposed for the TRANSFER project. The procedure involves 5 basic steps to assess tsunami risk and to produce tsunami risk zonation maps. The proposed approach is simple, transparent and therefore can be also useful for a comparison of different sites. Similar standardized approaches are widely accepted and applied in the other risk assessment applications such as for floods, landslides or hazards related with industrial sites. Therefore, it would be useful to have also tsunami risk assessment guidelines.

The method to assess tsunami risk presented in this report is based on two components: tsunami hazard and vulnerability that were weighted equally. In order to characterize the tsunami hazard, a combination of the depth and velocity product generated by the numerical modeling was used. The selection of these two variables seems to be appropriate because water depth and velocity are considered as the most significant factors controlling the tsunami hazard with respect to people loss. Other relevant characteristics for tsunami hazard include the tsunami wave height, magnitude, intensity or distance from the source and these can be considered in future research to refine the hazard classification. Another important aspect regarding the hazard characterization is to determine the hazard level rating, which is usually subjective. The vulnerability component of the risk was determined by the UNU-EHS, therefore this issue is not analyzed here and the reader in search of more detailed information is instead referred to UNU-EHS, 2009.

The outcome of our study provides a preliminary estimate of the tsunami hazard and risk for two scenarios: the “worst case” and the “5000 year event”. The selection of these two scenarios seems to be optimal for a preliminary study. However, if more scenarios are selected, a better comparison of the results can be done. The results itself show that a significant tsunami hazard and risk appears to exist for the city of Cádiz. This is in an agreement with a scientific paper by Damaskinidou-Georgiadou et al. 1987, who studied historical tsunamis in the southwestern coast of the Iberian Peninsula. The authors indicated that a significant tsunami such as known 1755 event can affect the coast with a return period of approximately 250-400 years. It is important to realize that the “worst case” scenario is an aggregation of the worst cases generated from the 5 seismic zones and therefore can be considered as unrealistic. It must be stressed that due to the conservative values used for the tsunami risk components, we judge the resultant risk to be overestimated. The “5000 year” event is more credible and we believe that it better estimates the potential risk in the city. It is also important to realize that the resultant tsunami risk maps are as accurate and detailed as the input hazard and vulnerability maps.

The tsunami risk zonation maps can be used by end-users (local authorities) as a preliminary tool for the identification of tsunami hot spot areas, or as risk indicator. Consideration of appropriate risk reduction measures should be particularly placed on the “very high” and “high” risk level areas. The maps can be further analyzed in a GIS environment in combination with other thematic maps to provide answers to specific questions based on the requirements from the end-users. Examples can include: “What kinds of establishments, e.g. residential, commercial, industrial are present in high risk areas? How far are these establishments from each other or from selected points of interest?” or similar questions.

The actual production of the tsunami risk zonation map is a very straightforward task in a GIS environment. However, the results of such analyses are highly dependent on the accuracy of the basic risk components used and its errors, which propagate into the final results. In particular, to generate tsunami hazard maps, it was necessary to combine the raster data from the numerical modeling with the thematic vector layer of the city district. The accuracy of these different types of maps was not always satisfactory. Therefore we had to use buffer analysis which decreased the accuracy of the resultant hazard maps. Other uncertainties are associated with the estimation of the vulnerability, in particular the number of people to be exposed and also wide range of the other factors that include each step in the entire process of the analysis, starting from the definition of sources and their characteristics, wave propagation and inundation modeling.

The estimated number of fatalities was calculated based on two factors: the tsunami wave height recorded on the coast and the number of people affected. There is a high uncertainty regarding these input parameters. The tsunami wave is obtained by numerical modeling and its weaknesses. The number of people is simply defined as the proportion of the population present in the affected area in each city district. Therefore temporal and spatial changes of the population are not considered.

Finally we have prepared some recommendations for future studies from the perspective of risk assessment that include:

- It would be desirable to perform a basic quantitative assessment of tsunami risk, such as a QRA. The obtained quantitative value of risk expressed as either individual or societal risk can be later compared with other sites or with risk (multi-risk) coming from different hazards. However, this can be a very difficult and possibly expensive task, which critically depends on data quality and availability.
- The methodologies used for tsunami risk analysis and its outcome differ due to different scales of the analysis. It would be useful to perform the risk analysis in the highest resolution scale feasible. We suggest that future research should consider a greater level of detail in the analysis by e.g. going from the level of city districts to the level of specific building blocks. The effort should be mainly concentrated on the areas of very high or high risk.

- Further research is needed to improve the tsunami hazard characteristics and their rating which is used for the purpose of risk assessment. This would make the hazard rating less subjective.
- Tsunami risk analyses may be extended to include new scenarios, or existing scenarios should be recalculated to consider the variability of the input parameters, e.g. using mean values of the physical tsunami parameters instead of their maxima.
- A systematic approach to tsunami hazard and risk assessment is required, and associated guidelines should be prepared.
- The production of tsunami evacuation maps showing evacuation zones and routes would be beneficial for the end users.

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ANNEX

They are differences relating to the definitions of risk and its estimation, therefore we have prepared a brief summary of some basic terms and definitions of risk that are used in this report. The summarized terminologies are consistent with the ISO/IEC Guide 73, 2000 or modified from the Australian Geomechanics Society (AGS 2007).

Consequence (C) is the outcome of an event. There can be more than one consequence from one event. With respect to a tsunami event the consequences are adverse.

Elements at Risk (E) are population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by the tsunami hazard.

Frequency is a measure of the number of occurrences of a repeating event per unit time. The concept of a return period or recurrence interval is commonly used to describe frequency in natural science. The reciprocal of the return period is the annual exceedance probability of the event (or indicative annual probability).

Hazard (H) is a potential source of harm. The tsunami hazard can be expressed as the probability of occurrence of a damaging tsunami of a given magnitude.

Qualitative Risk Analysis is an analysis which uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur.

Quantitative Risk Analysis is an analysis based on numerical values of the probability, vulnerability and consequences and resulting in a numerical value of the risk.

Quantitative Risk Assessment (QRA) is the generic term used for techniques which allow the risk associated with a particular activity to be estimated in absolute quantitative terms rather than in relative terms such as “high” or “low”. The most common results of a QRA are the *Individual Risk* and the *Societal Risk*. The Individual Risk is presented as contour lines on a topographic map with frequencies of 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7} and 10^{-8} per year, if in existence (CPR, 1999). The Societal Risk is plotted in the form of frequency-number curves (F-N curves). The x-axis represents the numbers of deaths N, while the y-axis represents the cumulative frequency of the events.

Risk (R) is the combination of the probability of an event and its consequence [ISO Guide 73]. In the case of natural hazards, this traditional concept of risk is extended to new components, such as vulnerability (V) of the elements at risk (E) within the affected area. The general expression for quantitatively estimating risk that can be applied also to tsunamis is therefore: $R = H \times C$, while $C = V \times E$.
Risk can also refer to the potential outcomes of an event occurring.

Risk Management, according to ISO/IEC Guide 73, coordinates activities to direct and control an organization with regard to risk. It comprises four components such as risk assessment, risk treatment, risk acceptance and risk communication.

- RISK MANAGEMENT (3.1.7)
  - RISK ASSESSMENT (3.3.1)
    - RISK ANALYSIS (3.3.2)
      - SOURCE IDENTIFICATION (3.3.4)
      - RISK ESTIMATION (3.3.5)
    - RISK EVALUATION (3.3.6)
  - RISK TREATMENT (3.4.1)
    - RISK AVOIDANCE (3.4.6)
    - RISK OPTIMIZATION (3.4.3)
    - RISK TRANSFER (3.4.7)
    - RISK RETENTION (3.4.9)
  - RISK ACCEPTANCE (3.4.10)
  - RISK COMMUNICATION (3.2.4)

Risk Acceptance is a decision to accept risk.

Risk Analysis is described as systematic use of information to identify sources and to estimate the risk. Risk analysis provides a basis for risk evaluation, risk treatment and risk acceptance.

Risk Assessment is an overall process of risk analysis and risk evaluation.

Risk Evaluation is the process of comparing the estimated risk against given risk criteria to determine the significance of the risk.

Risk Treatment (Mitigation) is the process of selection and implementation of measures to modify (reduce or eliminate) risk to human life and property based on tsunami risk assessments. It may include avoiding, optimizing, transferring or retaining risk.

Vulnerability (V) is understood in many different ways. For the purposes of this report we define vulnerability as a set of conditions and processes resulting from physical, social, economic, and environmental factors, which increase the susceptibility of a community to the impact of hazards.
(UN-ISDR terminology, http://www.adrc.or.jp/publications/terminology/top.htm#V)

European Commission

EUR 23956 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen
Title: Tsunami Risk Analysis Applied to the City of Cádiz
Author(s): Róbert Jelínek and Elisabeth Krausmann
Luxembourg: Office for Official Publications of the European Communities
2009 – 33 pp. – 21 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593

Abstract

This report provides tsunami risk analysis applied to the city of Cádiz. The results of the numerical modeling, hazard and vulnerability analyses are combined to produce tsunami risk zonation maps. In order to characterize the tsunami hazard, the University of Cantabria (UCa) together with the Instituto Geográphico Nacional (IGN) generated a series of inundation maps for return periods of 500, 1000, 5000 and 10 000 years. In addition to the specific probabilistic maps, a so-called "worst case" scenario was elaborated using a deterministic approach. The inundation maps served as a basis for the production of tsunami hazard zonation maps. The vulnerability assessment of the population was performed by the UNU-EHS and is based on the three components exposure, coping capacity and susceptibility. Having available the required hazard and vulnerability data allowed us to produce tsunami risk zonation maps for two selected scenarios which are 1) a "5000 year" event and 2) a "worst case" scenario. Furthermore, the tsunami mortality was estimated in order to illustrate the potential for fatalities distributed over the city districts. Present report indicates that significant risk exist for the city of Cádiz. The results of the tsunami risk analysis should help decision makers to effectively prepare, mitigate and manage this hazard. In the Cádiz city these are the Spanish Directorate of Civil Protection and Emergency Planning and Demarcación de Costas Andalucia Atlántico Dirección General de Costas.

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